

# Long-term experiences with XLPE cable systems up to 550 kV

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**Abstract** – All over the world, the use of cross-linked polyethylene as insulation material for high voltage power cables has been becoming standard. This is supported by the cleanness of the polyethylene material and the improvements in technical experiences at the cable manufacturers. For accessories, a high level of quality and reliability has been achieved with the technology of pre-fabricated and pre-tested insulation bodies of silicone rubber. In Switzerland, the first 400 kV cables with insulation of cross-linked polyethylene and accessories with silicone rubber insulation bodies were installed in the network at the beginning of the nineties in the last century. These systems are running smoothly up to date. All tests and many years of practical experiences have shown that solid cross-linked polyethylene insulation for high voltage and extra high voltage cables and silicone rubber insulation bodies for their accessories are characterised by long electrical lifetimes. To keep the potential of a long-term reliability, it is very important for the cables and accessories to be free of any partial discharges. The partial discharge measurements as routine tests for cables and accessories are therefore an important step for the quality of the cables and accessories. For electrical tests after installation, very good experiences have been made with UHF sensors at the terminations, directional coupling sensors and inductive sensors at the cross bonding links of the joints. For the cable, the monitoring of temperature showed valuable results. Once the cable system is energized and is subjected to electrical loads at network voltage, an electrical lifetime of well over 50 years can be expected.

## I. INTRODUCTION

Throughout the world, a growing use of cross-linked polyethylene (XLPE) as insulation material for high voltage power cables has taken place. For high voltage ( $\leq 220$  kV) and extra high voltage ( $> 220$  kV) cables, this trend is supported by the cleanness of the polyethylene material and the improvements in technical experiences at the cable manufacturers. For accessories, a high level of quality and reliability has been achieved with the technology of single piece pre-fabricated and pre-tested insulation bodies of silicone rubber (SiR).

In Switzerland, the first 400 kV cables with insulation of cross-linked polyethylene were installed in the power transmission network at the beginning of the nineties in the last century. The accessories used in these projects included single piece pre-fabricated and

pre-tested slip-on elements of SiR. These systems are running smoothly up to date.

In addition, methods for diagnostic measurements have seen further developments in recent years. Some of the cable systems have been retrofitted with sensors to enable applications like on-site partial discharge (PD) measurement for the accessories at nominal voltage.

The article describes the many years of experience that have now been accumulated with high voltage (HV) and extra high voltage (EHV) cable systems using cable insulations of XLPE and accessories with insulation bodies of SiR.

Based on all these positive experiences with HV and EHV cables and accessories in service and in pre-qualification tests for 420 kV, the article also reports on the continuing development of cable design due to optimization of wall thickness and field strengths.

## II. EXPERIENCES WITH HIGH VOLTAGE AND EXTRA HIGH VOLTAGE CABLE SYSTEMS

### A. Basics to electrical ageing in XLPE and SiR

When operational loads are applied, the electrical lifetime of HV and EHV cables with XLPE insulation and their accessories of SiR is determined by internal and external influences. With applied voltage, basically two electrical ageing processes takes place, partial discharge ageing and field ageing [1 – 4].

PD ageing due to discharge processes in cavities very quickly leads to an electrical breakdown of both, the XLPE and SiR insulation. It is vital that both, the cable and accessories of HV and EHV cable systems are free of PD. Therefore, PD measurements are a standard in routine testing as a post-production quality control for the cables and the silicone parts of the accessories [5].

Field ageing is described by the lifetime law as given in equation (1):

$$E^n \cdot t = \text{constant} \quad (1)$$

Whereas:

E: electric field

n: lifetime exponent

t: time

Accelerated field ageing is caused by spurs and occlusions in the XLPE insulation. At these areas, the electrical field is elevated and the electrical ageing process takes place more intensively. This is why PE materials of maximum purity and an extremely clean manufacturing process are prerequisites for the production of HV and EHV cable systems.

In detailed investigations on breakdown of XLPE cables, it was found that XLPE has a lifetime exponent of around 12 (Fig. 1) [1 – 4]. Experiences with real high voltage cables show that they withstand as least as long as the lifetime law proofs. This is even more valuable as the real cables additionally suffer higher temperatures, which further accelerates the electrical ageing process.

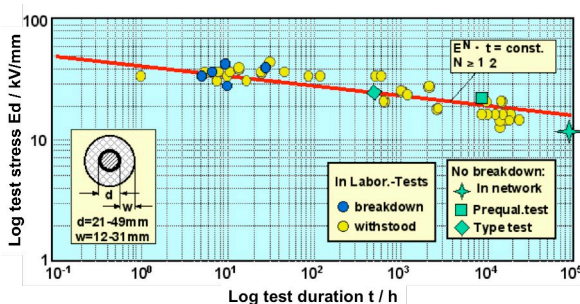


Fig. 1. Breakdown values and electrical ageing for XLPE cables according to [1 – 4] (red and blue) and values of practical experiences of Brugg Cables (green)

In detailed investigations on breakdown of silicone rubber (SiR) it was found that SiR has a lifetime exponent of greater than 40 (Fig. 2) [1, 6].

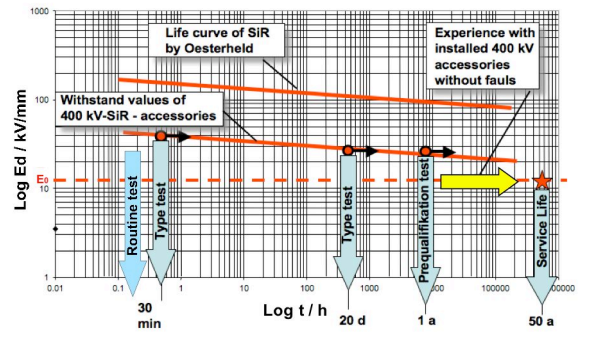


Fig. 2. Breakdown values and electrical ageing for SiR samples according to [1, 6] and values of practical experiences of Brugg Cables (blue and yellow arrows)

### B. Developing experiences of HV and EHV XLPE cables and SiR accessories

Many years of experiences in manufacturing HV cables with XLPE insulation and high voltage accessories of SiR up to 275 kV provided the best basis for the manufacture of 400 kV cables with XLPE insulation and accessories of SiR [7, 8] (Fig. 3).

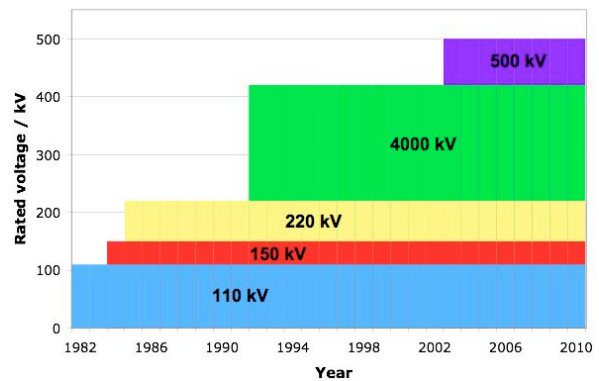


Fig. 3. Production of XLPE cables by Brugg Cables, Switzerland

The first 400 kV cable with insulation made of XLPE was produced in 1992 with a corrugated copper sheath. At Nordostschweizerische Kraftwerke, Switzerland, the first high voltage cable system with XLPE insulation in the 380 kV network were set up on the site of the Bonaduz/Grisons substation in spring 1993. The cable system initially comprised two outdoor terminations and about 200 m of cable. After five years of operating this cable system in the 380 kV network with no damage, the cable was cut in mid-length, a single piece prefabricated and pre-tested joint with SiR insulation body was introduced and the operation of the system was resumed.

After a further three years of operating in the network without faults, the joint was diagnostically tested with a new broadband partial discharge measurement system (Figs. 4 – 6) in 2001. This new testing process, based on the directional coupler sensor method, allows reliable recording of possible PD ageing processes in the joint, even in unscreened conditions [9 – 11]. The tests showed that the joint is free of PD after many years of operation at network volt-

age. With that, no damaging processes that could shorten the lifetime took place in the joint. After the measurement, network operation was continued until today without any problems.

Today, more than 4'000 km of HV cables and 20'000 pieces of SiR accessories up to 400 kV have been installed in the last 20 years and show excellent operating performance.

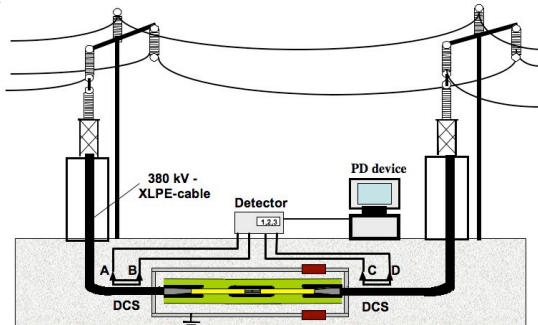


Fig. 4. Test set-up for on-site PD measurements on the 380 kV joint in Bonaduz, Switzerland

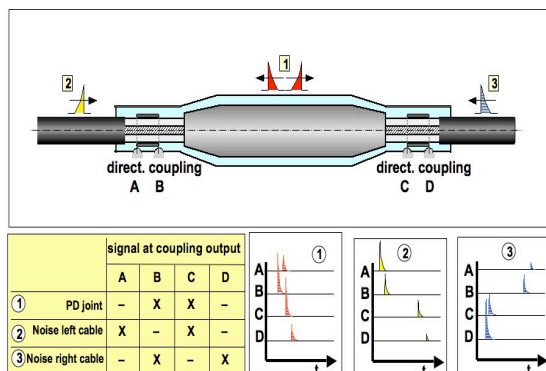


Fig. 5. Set-up and signals of directional couplings for PD detection



Fig. 6. On-site tests at the substation in Bonaduz, Switzerland

### III. IMPROVEMENTS

#### A. Cables

Over recent years, the qualitative properties of the XLPE compounds for HV and EHV cables have been substantially improved. The size and number of metallic and non-metallic impurities in the compound have been considerably reduced. They have now attained the levels shown in Table 1 [12].

Table 1: Highest permissible concentration (number/kg) of contaminants for selected size classes [12].

SIZE (μm)	50-70	70-100	100-200
HV	-	15	0
EHV	15	5	0

The size and number of impurities determine the electrical breakdown strength of the XLPE insulation. In the area surrounding the fault location, the field strength increases and locally accelerated field ageing takes place. The influence of the size of these impurities on the a.c. voltage breakdown strength was investigated using model cables [13] and real high-voltage cables (Fig. 7) [3]. Due to the volume effect with regard to breakdown probability and due to the desired failure probability for a cable in the energy distribution network of 1 fault per 50 year in 100 system kilometres, the values determined on model cables with insulation thickness of 1.5 mm only can not be used as a field strength for the purposes to determine the design of real high voltage cables. The critical sizes for impurities in the XLPE insulation for EHV cables are shown in relation to the maximum field strength on the conductor in Fig. 8 [3].

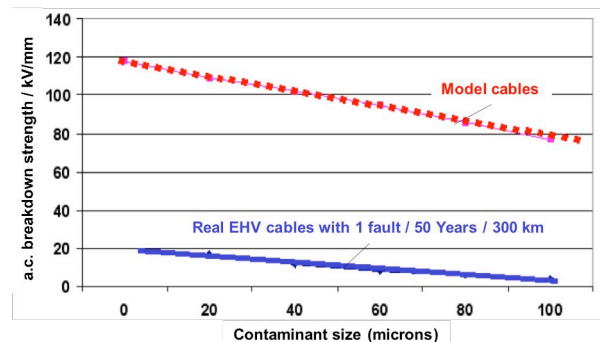


Fig. 7. Effect of metallic contaminant size on the a.c. breakdown strength of small model cables and real EHV cables [3, 13]

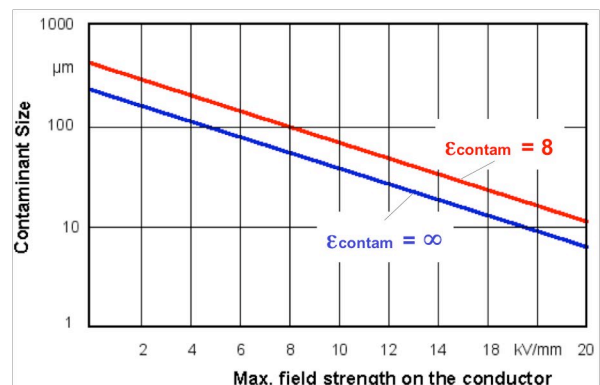


Fig. 8. Critical size of contaminant in the XLPE-insulation [3]

Fig. 9 shows the influence of the number and size of impurities with the same risk for electric breakdown. The results show that not only the size, but also the number of impurities per kg exerts a strong influence.



For these reasons and with the specified design field strength of  $>10$  kV/mm, insulation material of class EHV Super Clean with purity levels as shown in Table 1 is used to manufacture EHV cables. The proven high purity of the compound made it possible to use higher design field strengths and to reduce the insulating wall thicknesses (Fig. 10). With that, the maximum field strength always remains the same for a given voltage and the insulation wall thicknesses can be dimensioned in relation to the conductor cross-section (Fig. 11). The manufacture of EHV-XLPE cables using horizontal technology is now on a very high standard and is very reliable. Clean material handling and precise temperature and pressure monitoring during extrusion, dry curing and cooling guarantee a high standard of quality during the manufacturing process.

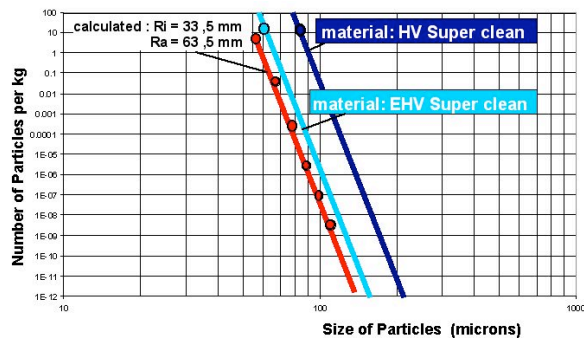


Fig. 9. No. of particles and size with same risk of el. breakdown

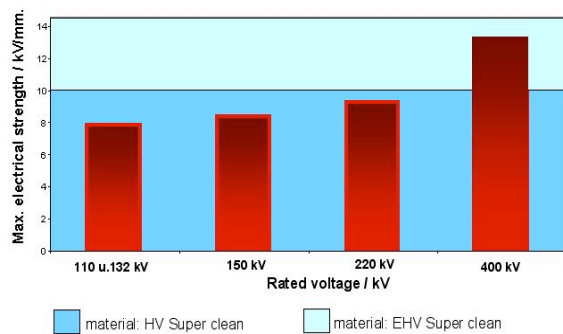


Fig. 10. Maximum electrical strength in XLPE cables

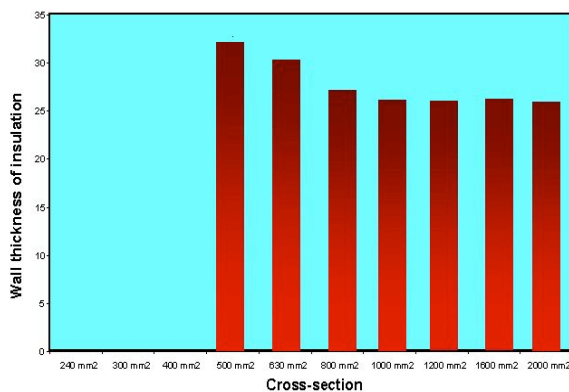


Fig. 11. Wall thickness of insulation of 400 kV XLPE cables

## B. Accessories

The reliability of the cable system also depends on the accessories. Over the years, it showed that an extreme high reliability can be achieved with prefabricated, pre-tested single piece slip on elements of SiR.

The slip-on elements consist of semiconductive deflectors, a semiconductive middle electrode (only for joint bodies) and the insulation compound. They ensure field grading between the semiconducting layers of the cable and the conductor clamp at a joint and the field grading at the end of the cable for a termination. The deflectors and middle electrode are made of solid semiconducting material. Although costly, this ensures that they function properly especially at fast BIL voltages (BIL = basic impulse insulation levels) and guarantees a long and reliable lifetime.

Beside many others, like very high temperature stability, high breakdown strength and high lifetime exponent, a main advantage of the SiR is the high flexibility. That ensures an optimum level of surface pressure on the cable and avoids any air gaps at the interface cable-insulation body, thus allowing a long reliable functioning. Due to the high stability of the SiR, the optimum surface pressure remains constant throughout the lifetime of the joint.

At a glance, the main advantages of the SiR are:

- Very high breakdown strength of  $> 23$  kV/mm at 50/60 Hz
- Excellent temperature stability of  $-50 - +180^{\circ}\text{C}$
- Very high life exponent of  $n > 40$
- Void free contact pressure on the cable at normal and elevated load due to high elasticity of SiR
- Easy to install due to excellent mechanical properties and elasticity

To keep all advantages of the SiR up to installation, the insulation bodies are produced in one-piece and in-house in a clean surrounding. To guarantee proper working, the insulation bodies must pass a final acceptance test. Every device is certified individually.

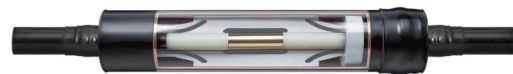


Fig. 12. Cross section of a joint with SiR insulation body



Fig. 13. Cross section of a GIS termination with SiR stress cone

#### IV. TESTS

After successful development and type tests on the cable system, a pre-qualification (PQ) test was carried out with 400 kV at CESI in Milan, Italy.

The test loop consisted of 120 m cable with an outer sheath of high-density polyethylene (HDPE) and laminated aluminium foil (1600 mm<sup>2</sup>) and 120 m cable with corrugated copper sheath (1600 mm<sup>2</sup>), two outdoor terminations (porcelain and composite insulators), two straight joints and two back-to-back GIS terminations. (Fig. 14). The cables were laid section by section in sand, pipe systems, in a tunnel and in air. An optical fibre was positioned along the test section to monitor temperature.

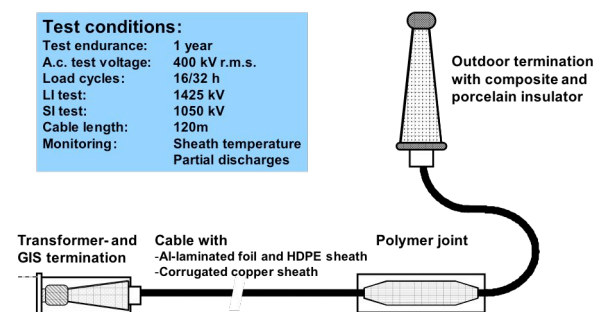


Fig. 14. 400 kV prequalification test set-up at CESI in Milan, Italy

The first heating cycles showed that there is better heat dissipation in the cable with HDPE outer sheath and laminated aluminium foil than in the cable with corrugated copper sheath (Fig. 15). Additional thermal insulation for the cable with HDPE outer sheath and laminated aluminium foil enabled the two cables to heat up to the maximum desired conductor temperature with the same heating current in the conductor.

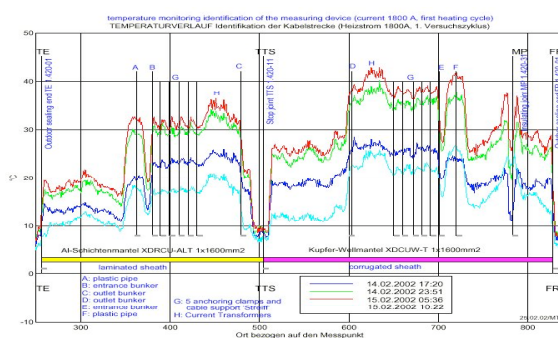


Fig. 15. Temperature profile of the cable during PQ test

To measure partial discharge during the test, PD sensors based on the directional coupler sensor method were built into all accessories. This solution was chosen as good experiences had been gained with these sensors for on-site PD measurements. In addition, another new Directly Modulating Discharge Measurement System that needs no active components in the accessories was built in for test purposes [14 – 16] (Fig. 16). Excellent experiences have also

been gained with on-site diagnostic PD measurements on GIS terminations during operation with a UHF-PD measuring method [17] and inductive sensors on the cross-bonding links in the cable systems [18].



Fig. 16. Directional coupling sensors and a directly modulating discharge measurement system

The PQ test was successfully completed in May 2003. Since spring 2009, a PQ test for a 500 kV XLPE-cable system is in operation.

#### V. CONCLUSIONS

Extensive tests and many years of practical experiences have shown that solid XLPE insulation for HV and EHV cables and SiR insulation bodies for their accessories are characterised by long electrical lifetimes.

However, if the electrical ageing is accelerated by partial discharges, early failures may occur. This is why it is very important for the cables and accessories to be free of any partial discharges. The PD measurement as a routine test for cables and prefabricated HV and EHV cable accessories is recommended as an important step towards quality and proves the long-term electrical stability.

For electrical tests after installation of a cable system, the standards do not generally specify a PD measurement. However, if required, very good experiences have been made with the method of UHF sensors at the terminations and inductive sensors on the cross bonding links at the joints. For the cable, the monitoring of temperature showed good results.

Once the cable system is energized and is subjected to electrical loads at network voltage, an electrical lifetime of well over 50 years can be expected.

#### VI. REFERENCES

- [1] W. Weissenberg, U. Rengel, R. Scherer, EHV XLPE Cable Systems up to 400 kV – More than 10 Years Field Experience -, CIGRE 2004, paper B1-102, 2004
- [2] E. Peschke, R. v. Olshausen, Cable Systems for High and Extra-High Voltage, Development, Manufacture, Testing, Installation and Operation of Cables and their Accessories, Publicis MCD Verlag, Erlangen and Munich, 1999
- [3] W. Weissenberg, Einfluß makroskopischer Fehlstellen auf die elektrische Alterung von Polyethylenkabeln bei Wechselspannungsbelastung, Thesis TU Dresden, 1986
- [4] R. v. Olshausen, W. Weissenberg, The electrical long-term performance of cross- linked polyethylene, 30 WIRE 5/2001

- [5] W. Weissenberg, M. Kuschel, Test methods for SiR-accessories used in high voltage cables up to 400 kV, 6th Jicable, Paris, 2003
- [6] J. Oesterheld, Dielektrisches Verhalten von Silikongummi-Isolierungen unter elektrischer Hochfeldbeanspruchung, Thesis, Technische Universität Dresden, 1994
- [7] R. Badent, T. Eisebraun, R. Hansen, A. Schwab, U. Schwing, VPE-Kabelanlage für eine 220-kV-Energieableitung, Elektrizitätswirtschaft, Heft 6, 1998
- [8] L. Ritter, R. Scherer, M. Laurent, R. Bautz, H. Zimmermann, HV cable networks in Switzerland – Particularities and Experience, CIGRE session 1994, Paper 21-104, 1994
- [9] D. Pommerenke, T. Strehl, R. Heinrich, W. Kalkner, F. Schmidt, W. Weißenberg, Discrimination between Internal PD and other Pulses using Directional Coupling Sensors on High Voltage Cable Systems, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.6, No 6, December 99, pp. 814-824, 1999
- [10] D. Pommerenke, T. Strehl, W. Kalkner, Directional Coupler Sensor for Partial Discharge Recognition on High Voltage Cable Systems, International Symposium On High Voltage, ISH 1997, Montreal, Canada, 1997
- [11] D. Pommerenke, I. Krage, W. Kalkner, E. Lemke, P. Schmigel: On-site PD measurement on high voltage cable accessories using integrated sensors, International Symposium On High Voltage, ISH 95, Graz, Austria, 1995
- [12] J.-O. Boström, A. Campus, R. N. Hamton, E. Marsden, Reliable HV & EHV XLPE cables, CIGRE, Paper 21-105, 2002
- [13] J.-O. Bostrom, E. Marsden, R. N. Hampton, U. Nilsson, H. Lennartsson, Electrical Stress Enhancement of Contaminants in XLPE Insulation Used for Power Cables, IEEE Electrical Insulation Magazine July/August 2003 – Vol. 19, No.4, 2003
- [14] D. Pommerenke, K. Masterson, A Novel Concept for Monitoring Partial Discharge on EHV-Cable System Accessories Using no Active Components at the Accessories, Dielectric Materials, Measurements and Applications Conference Publication No. 473, © IEE 2000
- [15] K. D. Masterson, D. R. Novotny, K. H. Cavecy, Standard antennas designed with electrooptic modulators and optical-fibre linkage, Intense Microwave Pulses IV, H.E. Brand, ed, Proc. SPIE, Vol. 2834 1996, pp. 188-196, 1996
- [16] A. Donval, E. Toussaere, R. Hierle, J. Zyss, Polarization insensitive electro-optic polymer modulator, J. applied Physics, Vol. 87, No.7, April 2000, pp. 3256-3562, 2000
- [17] E. Lemke, H. Elze, W. Weissenberg, Experience in PD diagnosis tests of HV cable terminations in service using the ultra-wide band PD probing, 13th ISH 03, Delft, 2003
- [18] W. Weissenberg, F. Farid, R. Plath, K. Rethmeier, On-Site PD Detection at Cross-Bonding Links of HV Cable Systems, CIGRE 2004